

# VISCOSITY MODELING AND PREDICTION OF RESERVOIR FLUIDS: FROM NATURAL GAS TO HEAVY OILS

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## Abstract

Viscosity and density are key properties for the evaluation, simulation and development of petroleum reservoirs. In previous works, the friction theory (*f-theory*) models have already been shown capable of delivering simple and accurate viscosity modeling results of petroleum reservoir fluids with molecular weights up to around 200 g/mol. As a base, the *f-theory* approach requires a compositional characterization procedure to be used in conjunction with a van der Waals type of equation of state (EOS). This is achieved using simple cubic EOS, which are widely used within the oil industry. In this work, the *f-theory* approach is further extended to the viscosity modeling of heavy reservoir fluids with viscosities up to thousands of mPa s. Essential to the presented extended approach is first achieving accurate *pvT* results for the EOS characterized fluid. In particular, it has been found that for accurate viscosity modeling of heavy oils, a compressibility correction in the way the EOS is coupled to the viscosity model is required. With the approach presented in this work the *f-theory* potential for the viscosity modeling of reservoir fluids is extended to practically all kind of reservoir fluids; from light ones to heavy ones. Additionally, the approach has been completed with an accurate density modeling scheme

**KEYWORDS:** Characterization, equation of state, density, *f-theory*, modeling, petroleum, viscosity.

## 1. INTRODUCTION

In previous works, the friction theory (*f-theory*) [1] for viscosity modeling has been applied to the accurate viscosity prediction of light reservoir fluids (natural gas) [2] and the accurate modeling and prediction of denser reservoir fluids, with molecular weights up to around 200 g/mol [3]. However, the viscosity modeling of heavy reservoir fluids, molecular weights up to more than 400 g/mol and reservoir conditions viscosity in the order of thousands of mPa's, remained untouched. Thus, while preserving most of the simplicity and the accuracy of the original formulation, in this work, the *f-theory* approach is further extended to heavy reservoir fluids. Furthermore, the scheme illustrated here is still based on the kind of simple cubic equations of state that are commonly used in the oil industry.

The *f-theory* for viscosity modeling consists in simple but accurate viscosity models that take advantage of the repulsive and attractive pressure terms in van der Waals type equations of state (EOS), such as the Soave-Redlich-Kwong (SRK) EOS, [4] or the Peng-Robinson (PR) EOS [5]. In subsequent works [6, 7] generalized *f-theory* one-parameter models have been developed to be used in conjunction with some of the most popular EOS. These models can accurately represent the viscosity of a large number of pure hydrocarbons and, using simple mixing rules and pure-component parameters, accurately predict mixture viscosities. The one-parameter *f-theory* models have been further extended to the accurate viscosity prediction and modeling of characterized crude oils [3]. In an oil characterization procedure the light fraction, up to C<sub>6</sub>, is normally described in terms of 11 well-defined components: N<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>S, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, i-C<sub>4</sub>, n-C<sub>4</sub>, i-C<sub>5</sub>, n-C<sub>5</sub> and C<sub>6</sub>. However, the heavy (C<sub>7+</sub>) oil fraction is characterized in terms of a given number of pseudocomponents for which some scaling parameters are derived so that the phase behaviour is correctly reproduced. In this work, a new characterization procedure [8], which is a generalization of a previous work [9] is used.

## 2. OIL PVT CHARACTERIZATION

The core of the viscosity modeling work presented here is the oil characterization into a number of compounds and pseudo-compounds capable of, in conjunction with an EOS, delivering adequate phase and viscosity behaviour performance. In sake of completeness, a recently proposed characterization procedure [8] for reservoir fluids is summarized in this section. The procedure consist of characterizing the heavy oil fractions by distributing the C<sub>7+</sub> mass fraction according to a chi-square distribution function with  $p$  degrees of freedom (CS( $p$ )) that best represents the fluid mass distribution of the C<sub>7+</sub> fraction. The general mathematical form of the CS( $p$ ) distribution function is:

$$f_{\text{dis}} = \frac{2^{p/2}}{\Gamma(p/2)} e^{-s^2/2} s^{\frac{p}{2}-1} \quad (1)$$

where  $s$  can be considered as a mass distribution variable. It is required that

$$\int_0^{s_0} f_{\text{dis}} ds = M_6 \quad (2)$$

where  $M_6$  represents the fluid total light mass fraction up to the  $C_6$  fraction and  $s_0$  is the value of  $s$  that satisfies Eq. (2). That is

$$M_6 = \frac{1}{MW_T} \sum_i x_i MW_i \quad (3)$$

where summation over  $i$  covers all light compounds in a given oil sample up to hexanes and  $MW_T$  is the total molecular weight of the fluid. Then, the  $C_{7+}$  fraction is characterized in an  $m$  number of heavy fractions  $F_i$  of mass fraction  $fm_i$  according to

$$fm_i = \int_{s_{i-1}}^{s_i} f_{dis} ds \quad (4)$$

Finally, the molecular weight  $MW_i$  of the fraction  $F_i$  is given by

$$MW_i = \overline{MW} \hat{s}_i \quad (5)$$

where  $\hat{s}_i$  represents the center of mass for the  $F_i$  fraction and  $\overline{MW}$  is a scaling value so that the total mass balance is satisfied. That is,  $\hat{s}_i$  is calculated with the equation

$$\hat{s}_i = \frac{1}{fm_i} \int_{s_{i-1}}^{s_i} s f_{dis} ds \quad (6)$$

and, from Eq. (5) and a mass balance, it can be shown that  $\overline{MW}$  is given by

$$\overline{MW} = \frac{MW^+}{(1 - M_6)} \sum_{i=1}^m \frac{fm_i}{\hat{s}_i} \quad (7)$$

where  $MW^+$  is the  $C_{7+}$  fraction molar mass.

For the  $m$  lumped compound groups and heavy fractions, the scaling parameters that are required in the EOS are estimated after empirical equations based on the properties of normal alkanes. The empirical equations are

$$T_{c,i} = -423.587 + 210.152 \ln(MW_i) \quad (8)$$

$$P_{c,i} = f_c \exp(9.67283 - 4.05288 MW_i^{0.1}) \quad (9)$$

$$\omega_i = \exp\left[8.50471 - \frac{15.1665}{MW_i^{0.1}}\right] \quad (10)$$

where  $T_c$  is the critical temperature,  $P_c$  the critical pressure and  $\omega$  the acentric factor for the fraction  $i$ . Here,  $MW$  is given in g/mol to obtain  $T_c$  in K and  $P_c$  in bar. In Eq. (9),  $f_c$  represents a perturbation factor away from the  $f_c = 1$  value that corresponds to the fit of

n-alkanes. This perturbation factor is iteratively modified until the fluid saturation pressure is matched. It should be pointed out that for the well-defined light compounds (i.e. methane, ethane, etc.) tabulated values are used. Also, in case some light compounds have been lumped together, Eqs. (8-9) can be used to estimate the lumped compounds scaling parameters by setting  $f_c = 1$ .

In addition to matching the saturation pressure, a P  neloux volume translation [10] proposed in Ref. [8] is used in conjunction with this procedure. The volume correction delivers accurate density modeling results and consists in shifting the volume from the volume  $v$  obtained with the EOS to a translated volume  $v'$ ,

$$v' = v + c \quad (11)$$

where, in the case of reservoir fluids,  $c$  has been proposed to be estimated by the following mixing rule

$$c = K_v \sum_{h.fr.} x_i MW_i \quad (12)$$

In Eq. (12), the summation only includes the heavy fraction (*h.fr.*) pseudocomponents corresponding to  $C_{7+}$  and  $K_v$  represents a characteristic volume constant for the fluid. The constant  $K_v$  is obtained by tuning against high-pressure density data measured at and above the saturation pressure.

### 3. OIL VISCOSITY CHARACTERIZATION OF NORMAL OILS

A detailed description of the viscosity modeling procedure for normal crude oils using *f-theory* models is readily available [3] and only a brief summary will be given here. The application of the *f-theory* to the viscosity modeling of crude oils consists in applying the one-parameter *f-theory* models to previously characterized reservoir fluids. In the friction theory the total viscosity  $\mu$  is separated into a dilute gas viscosity term  $\mu_0$  and a residual friction term  $\mu_f$ ,

$$\mu = \mu_0 + \mu_f \quad (13)$$

The dilute gas viscosity  $\mu_0$  is defined as the viscosity at the zero density limit and, for systems such as reservoir fluids, it can be accurately estimated with the empirical model by Chung et al. [11]. The residual term  $\mu_f$  is related to friction concepts of classical mechanics and can be approximated by

$$\mu_f = \mu_r p_r + \mu_a p_a + \mu_{rr} p_r^2 \quad (14)$$

where  $p_a$  and  $p_r$  are the van der Waals attractive and repulsive pressure contributions in the mixture. These contributions can be estimated from simple cubic EOS, such as the SRK EOS or the PR EOS, among others. In the case of alkanes and other non-polar fluids, including reservoir fluids, generalized models depending on one characteristic fluid viscosity scaling parameter have been further developed [6, 7]. The formulation of the one-parameter general models is as follows:

$$\bar{\mu}_f = \bar{\mu}_c \left[ \bar{\mu}_r \frac{P_r}{P_c} + \bar{\mu}_a \frac{P_a}{P_c} + \bar{\mu}_{rr} \frac{P_r^2}{P_c^2} \right] \quad (15)$$

where  $\bar{\mu}_c$  is the characteristic fluid viscosity scaling parameter and  $P_c$  is the critical pressure. The  $\bar{\mu}_r$ ,  $\bar{\mu}_a$  and  $\bar{\mu}_{rr}$  parameters are only dependent on the reduced temperature and have been parameterized into universal constants that are related to a specific EOS. In the case of mixtures, the value of the mixture friction coefficients is predicted using the mixing rules suggested in Ref. [6]. For the EOS, in principle, the mixing rules that best describe the fluid phase behaviour should be used.

For crude oils, once the fluid has been properly characterized, the determination of the viscosity scaling parameters is similar to the one for the  $pvT$  scaling parameters. That is, for well-defined light compounds (i.e. methane, ethane, etc.) reported tabulated values [6] are used. In case some light compounds (up to  $C_6$ ) have been lumped together, the following modified Uyehara-Watson equation [3, 12] may be used

$$\bar{\mu}_{c,i} = 7.94830 \cdot 10^{-4} \frac{\sqrt{MW_i} P_{c,i}^{2/3}}{T_{c,i}^{1/6}} \quad (16)$$

where the units in Eq. (16) are  $MW$  in g/mol,  $P_c$  in bars and  $T_c$  in K to obtain  $\bar{\mu}_c$  in mPa s. For the pseudocomponents that correspond to the  $C_{7+}$  fraction Eq. (16) is relaxed by substituting the model constant for an adjustable common parameter  $K_c$  that can be taken as a viscosity characterization parameter for all of the pseudocomponents in the heavy fraction, i.e.

$$\bar{\mu}_{c,i} = K_c \frac{\sqrt{MW_i} P_{c,i}^{2/3}}{T_{c,i}^{1/6}} \quad (17)$$

Furthermore, it has been shown that substitution of equations (16) and (17) into the one-parameter friction theory models results in a simple linear equation [3] of the form

$$\bar{\mu} = \bar{\mu}_I + K_c \bar{\mu}_{II} \quad (18)$$

where  $\bar{\mu}_I$  and  $\bar{\mu}_{II}$  are well defined numbers [3]. Clearly, although to solve for  $K_c$  one viscosity point is enough, it has also been found that the best results are obtained if  $K_c$  is estimated by an optimization procedure using viscosity data from the one phase region above the fluid saturation pressure.

The approach summarized in this section has been extensively shown to be able to deliver accurate viscosity modeling results for reservoir fluids with  $MW$  up to around 200 g/mol [3, 8, 9, 13]. However, as a reservoir fluid becomes heavier, cubic EOSs show systematic compressibility related deterioration in the quality of the results. To illustrate this, three fluids, a normal one (Oil 1), a slightly heavier one (Oil 2) and a heavy one (Oil 3) have been chosen. The main properties for these three oils are summarized in Table 1, along with three other heavy oils, after a mass characterization into a total of 10 compounds using an optimal  $CS(p)$  function [8] and the  $pvT$  tuning procedures have been carried out. That is, after lumping some of the light fractions, carrying out the mass characterization procedure for the  $C_{7+}$  fractions into four heavy

pseudocomponents and tuning for the saturation pressure using the PR EOS. For the PR EOS the regular van der Waals mixing rules (linear in  $b$  and quadratic in  $a$ ) have been used with the following binary parameters: 0.02 for  $N_2-C_1$ ; 0.06 for  $N_2-(C_2-C_3)$ ; 0.08  $N_2-C_{i>3}$ ; 0.12  $CO_2-C_1$ ; 0.15  $CO_2-C_{i>1}$ ; 0 for all hydrocarbon-hydrocarbon interactions ( $C_i$  and  $F_i$  compound groups). As Fig. 1 shows, the viscosity modeling results after tuning  $K_c$  with data above the saturation pressure are qualitatively and quantitatively good for Oil 1 and, to some extent also for Oil 2, but not so for Oil 3. In the case of Oil 3 it can be seen that the PR EOS based  $f$ -theory model fails to correctly match the viscosity versus pressure slope. This problem is consistently found in heavy fluids and it is thought to be related to the simple mathematical structure of the repulsive term in the cubic EOS.

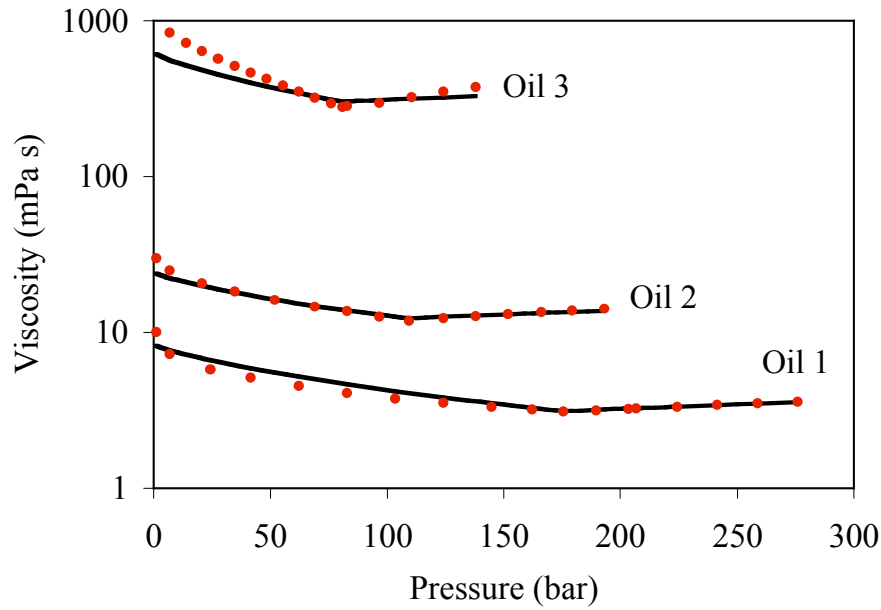


Figure 1. Viscosity modeling results for the viscosity characterization constant  $K_c$  tuned with data above the saturation pressure. Model prediction: solid lines; experimental data: points.

#### 4. COMPRESSIBILITY CORRECTION FOR HEAVY OILS

##### 4.1 Volume correction

The friction theory takes advantage of the repulsive-attractive balance built into a van der Waals type of EOS. This has been shown to work extremely well for a large variety of fluids for which the EOS gives reasonably good performance. However, for highly dense fluids the simple mathematical form of a van der Waals type of EOS, particularly the repulsive term, is not adequate. Essentially, as illustrated in the Oil 3 example depicted in Fig. 1, the response that the repulsive term gives to the viscosity with the pressure is not as sharp (lower slope) as experimentally observed. Thus, a correction procedure that does not require a mathematical modification of the EOS has been devised. In order to correct the compressibility discrepancy, it has been found that a simple and efficient method consists in displacing the volume by a value of  $\Delta v$

$$\tilde{v} = v - \Delta v \quad (19)$$

and then estimating the viscosity friction contribution using the corrected volume. That is,

$$\bar{\mu}_f = \bar{\mu}_r \tilde{p}_r + \bar{\mu}_a \tilde{p}_a + \bar{\mu}_{rr} \tilde{p}_r^2 \quad (20)$$

where  $\tilde{p}_r$  and  $\tilde{p}_a$  are the repulsive and attractive pressure contributions estimated at the displaced corrected volume  $\tilde{v}$ .

Table 1. Main characteristic parameters for one normal oil (Oil 1) and five heavy oils (Oils 2 through 6).

	Oil 1		Oil 2		Oil 3		Oil 4		Oil 5		Oil 6	
	CS(6)		CS(6.5)		CS(6)		CS(9)		CS(7.5)		CS(7.5)	
	<i>x</i>	<i>MW</i>	<i>x</i>	<i>MW</i>	<i>x</i>	<i>MW</i>	<i>x</i>	<i>MW</i>	<i>x</i>	<i>MW</i>	<i>x</i>	<i>MW</i>
N <sub>2</sub>	0.0007	28.02	0.0113	28.02	0.0002	28.02	0.0035	28.01	0.0004	28.02	0.0004	28.02
CO <sub>2</sub>	0.0006	44.01	0.0003	44.01	0.0039	44.01	0.0004	44.01	0.0121	44.01	0.0216	44.01
C <sub>1</sub>	0.4206	16.04	0.2786	16.04	0.2771	16.04	0.2556	16.04	0.1892	16.04	0.1992	16.04
C <sub>2</sub> -C <sub>3</sub>	0.0176	31.66	0.0132	33.38	0.0054	36.82	0.0003	32.07	0.0008	37.08	0.0013	32.23
C <sub>4</sub> -C <sub>5</sub>	0.0075	66.17	0.0097	64.93	0.0105	67.07	0.0001	65.74	0.0018	65.92	0.0010	67.94
C <sub>6</sub>	0.0060	85.64	0.0054	86.18	0.0161	86.18	0.0002	84.00	0.0023	86.18	0.0021	86.18
F <sub>1</sub>	0.2411	168.22	0.3029	193.03	0.3165	334.54	0.3091	252.56	0.3486	300.42	0.3389	275.45
F <sub>2</sub>	0.1446	280.51	0.1781	328.31	0.1769	598.61	0.1942	402.02	0.2059	508.72	0.2014	463.51
F <sub>3</sub>	0.1001	405.24	0.1239	471.84	0.1205	878.64	0.1424	548.12	0.1461	717.09	0.1430	652.65
F <sub>4</sub>	0.0612	663.26	0.0766	762.79	0.0729	1451.60	0.0941	829.31	0.0929	1127.86	0.0910	1025.86
<i>MW<sub>T</sub></i> (g/mol)	170.60		240.20		430.42		316.55		422.85		377.88	
<i>T</i> (K)	330.40		345.93		341.48		308.15		322.05		322.05	
<i>P<sub>sat</sub></i> (bar)	175.50		109.28		80.67		69.82		45.85		47.23	
<i>f<sub>c</sub></i>	1.4026		1.3358		1.3039		1.2876		1.1812		1.0798	

#### 4.2 Mixing rules

Although the correction described in Eq. (19) is applied in order to correct the viscosity versus pressure slope in the high-pressure one phase region, some mixing rules for  $\bar{\mu}$  are necessary for the region below the saturation pressure. Thus, the following mixing rule has been found to provide satisfactory results:

$$\bar{\mu} = K_z \sum_i x_i MW_i^{1/3} \quad (21)$$

where the summation applies only to the pseudocomponents of the heavy oil fraction.

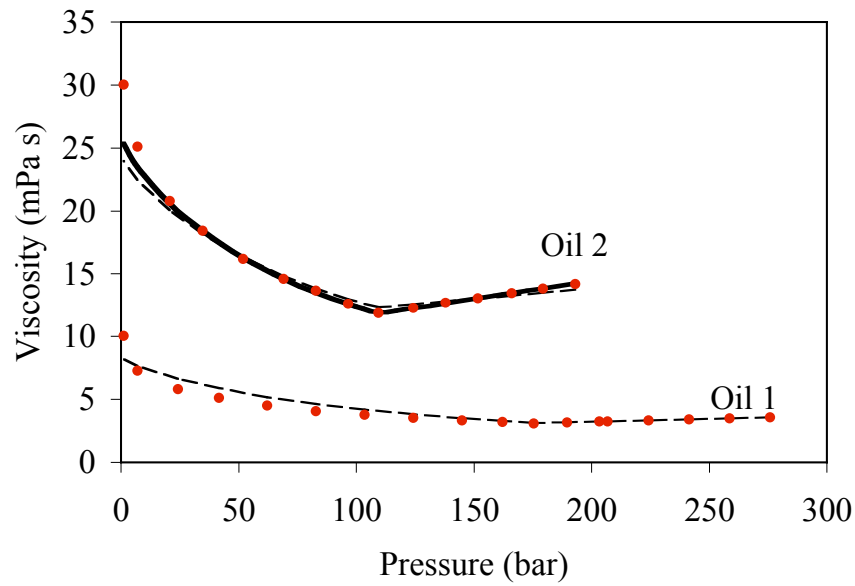


Figure 2. Modeling results for Oils 1 and 2. Oil 2 corrected model: solid line; original model: dashed lines; experimental data: points.

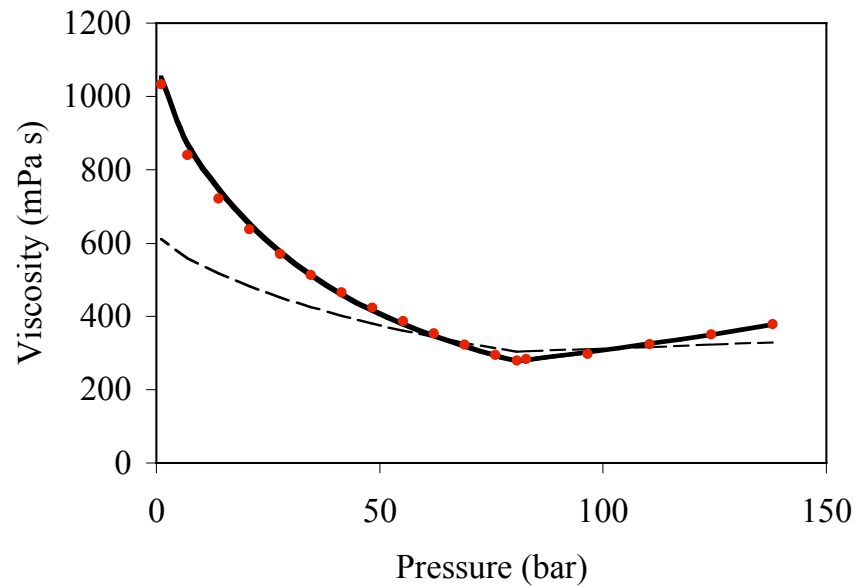


Figure 3. Modeling results for Oil 3. Corrected model: solid line; original model: dashed lines; experimental data: points.

## 5. RESULTS

In spite of the simplicity of the approach presented in the previous section, the introduction of the described correction results in correct viscosity modeling behaviour above the saturation pressure (compressibility correction) and accurate viscosity prediction below the saturation pressure. Figures 2 and 3 illustrate the modeling results for the fluids previously presented in Fig. 1. In Fig. 2 it can be appreciated that the correction is not required for Oil 1 and it has a slight improvement in the quality of the

Oil 2 results. However, as Fig. 3 indicates, the effect of the correction is remarkable in the case of the heavy Oil 3.

This work approach for the viscosity modeling of heavy oils is further illustrated in the cases of the Oils 4, 5 and 6 that are depicted in Fig. 4. Clearly, the modeling results above the saturation pressure are visibly accurate while the predictions below the saturation pressure are within experimental uncertainty. It is worth noticing that the uncertainty in the experimental viscosity measurements of heavy oils below the saturation pressure is extremely high. This is particularly affected by the uncertainty in the equilibrium curve determination and the high possibility of solid formation.

In addition to the viscosity results obtained with this work modified *f-theory* approach, the density modeling scheme discussed in section 2 has also been applied to oils 1, 5 and 6 – density data for oils 2, 3 and 4 are not available. For oils 1, 5 and 6, the density modeling results above the saturation pressure and the corresponding density predictions below the saturation pressure are shown in Fig. 5. In all cases, the absolute average deviation (AAD) density modeling results are better than 0.5%.

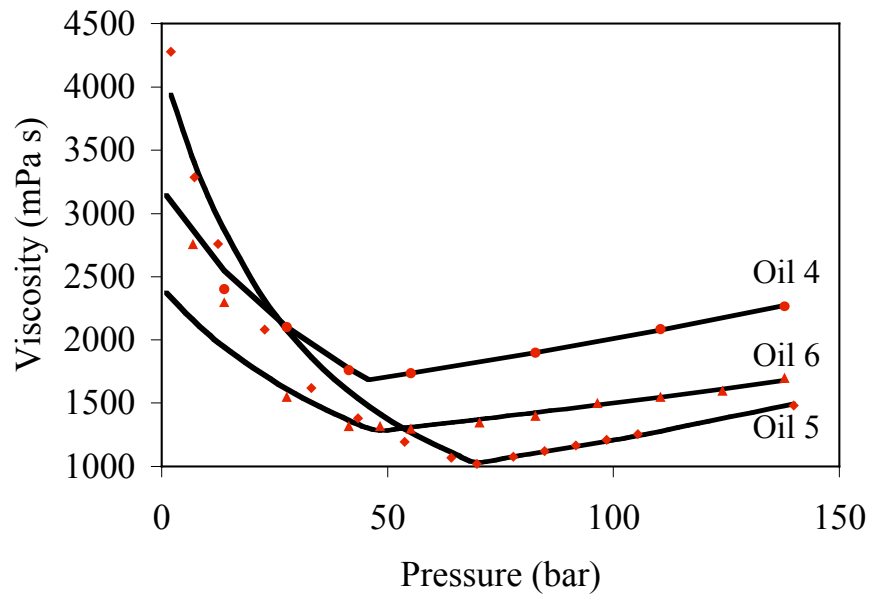


Figure 4. Viscosity modeling results for Oils 4, 5 and 6. Corrected model: solid lines; experimental data: points.

Finally, the viscosity and density parameters corresponding to all of the examples presented in this work are reported in Table 2.

Table 2. Viscosity and density parameters.

	Oil 1	Oil 2	Oil 3	Oil 4	Oil 5	Oil 6
$K_v(\text{cm}^3/\text{g})$	0.120213	N/A	N/A	N/A	-0.164751	-0.267768
$*K_c \cdot 10^4$	7.46396	11.0402	7.34572	34.9945	85.1331	115.416
$K_z(\text{cm}^3/\text{g})$	0	1.12254	2.38373	2.12622	1.48187	1.38409

\*Units as defined for Eq. (16).

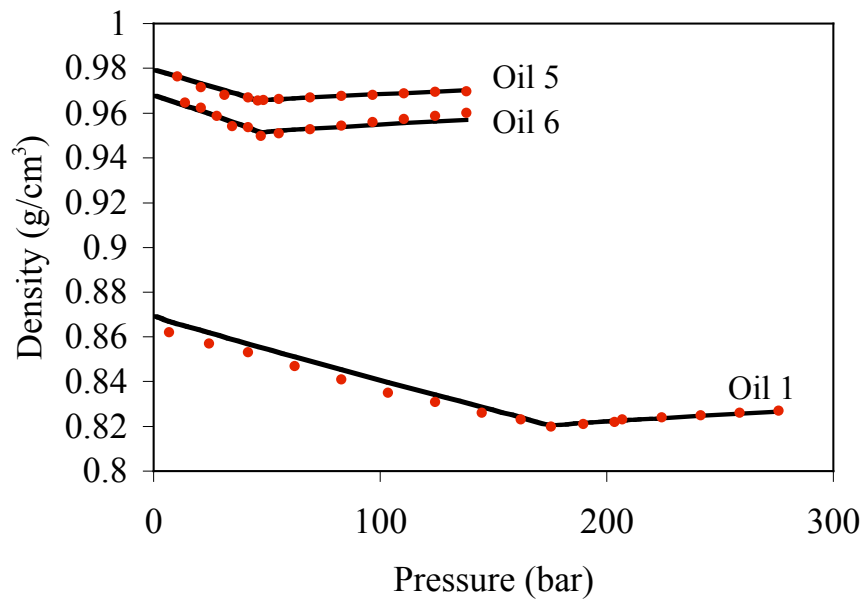


Figure 5. Density modeling results for Oils 1, 5 and 6. Model: solid lines; experimental data: points

## 5. CONCLUSIONS

In this work, the previously developed *f-theory* viscosity modeling approach for reservoir fluids [3] has been successfully extended to practically the full range of reservoir fluids that are of interest to the oil industry. Altogether, a comprehensive *f-theory* viscosity modeling approach that goes from the plain accurate viscosity prediction of light natural gases [2] to the accurate modeling of heavy oils presented in this work, covering practically six orders of magnitude in viscosity, has been accomplished. The comprehensive approach to the viscosity modeling of reservoir fluids that is round up with this work, is built on the same type of simple tools, i.e. cubic EOS, that are commonly used in the oil industry. Therefore, the incorporation of this approach into other more elaborated oil industry tools, such as reservoir simulators, is straightforward. Furthermore, an efficient implementation of the *f-theory* viscosity modeling approach into a compositional reservoir simulator would not represent any substantial additional computational cost, since it can take advantage of already computed properties. However, the prediction capabilities of the *f-theory* model in the simulation of scenarios with substantial compositional changes, such as gas injection or reservoir depletion, represent a clear advantage over other viscosity modeling approaches that are commonly used in the oil industry, such as the Lohrenz-Bray-Clark (LBC) model [14].

In addition to the *f-theory* viscosity modeling, the approach has been completed with an accurate density modeling scheme [8]. The density modeling scheme that is also presented in this work completes two of the most important needs in the oil industry: modeling and prediction of reservoir fluids viscosity and density. As long as the presented density modeling approach is applied away from critical conditions, as it is the case for most dense reservoir fluids and certainly for heavy oils, this P  neloux based density modeling approach is capable of delivering accurate results. In all cases studied in this and previous works [8, 13] the presented density modeling approach delivers an AAD of the order of 0.5% for the liquid phase of a wide range of reservoir fluids.

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